The Performance of Mesoscale Models at Sub-Kilometer Grid Spacing and Implications for Air Quality Modeling for Urban Valleys

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Objective

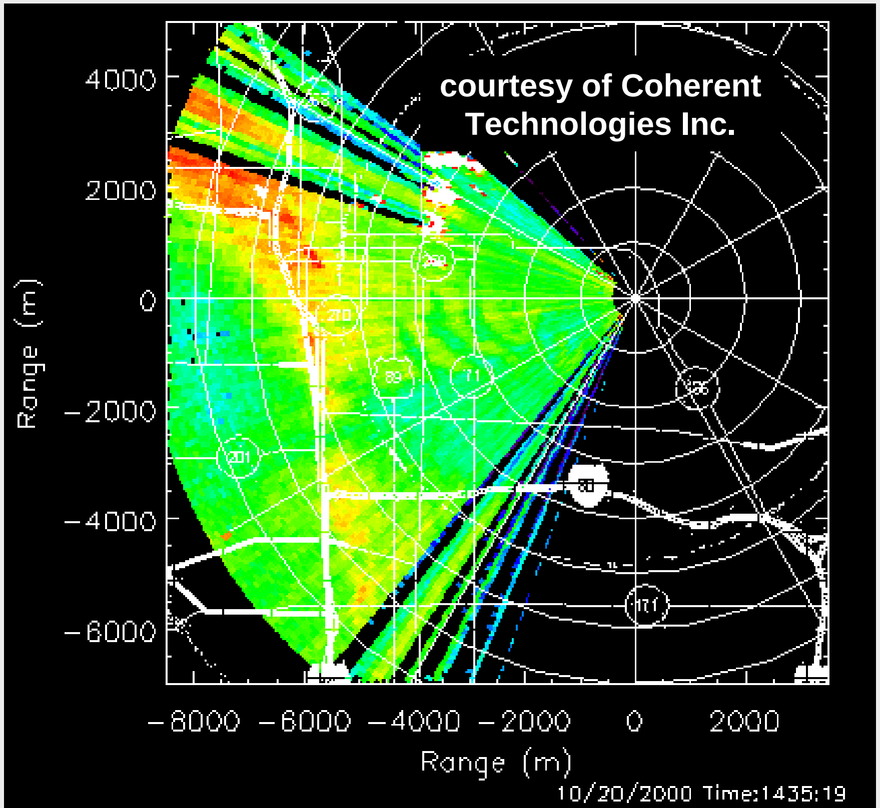
Horizontal grid spacing used by mesoscale and global meteorological models are typically O(10 km) and O(100 km), respectively. Many of the errors are often attributed to coarse spatial resolution.

In this study, we use the October 2000 VTMX field campaign observations to evaluate meteorological parameters important to transport and mixing processes predicted by 3 mesoscale models that use horizontal grid spacings < 1 km. This spatial resolution should be sufficient to resolve the dominant circulations within the Salt Lake Valley.

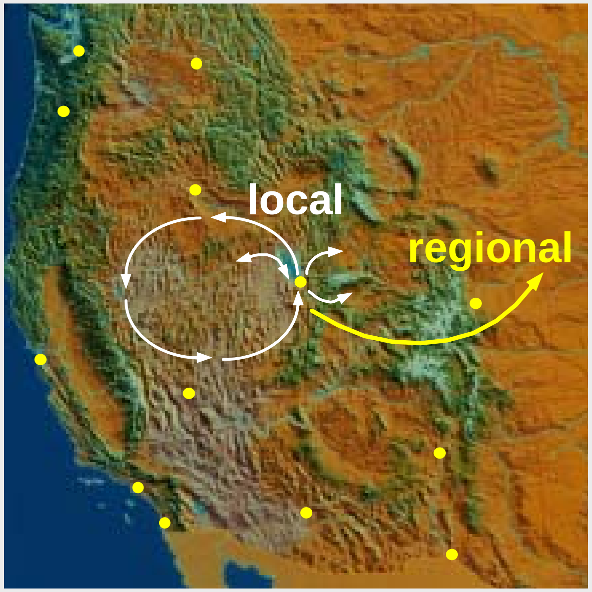
- **How well do these models perform?**
- **What improvements, if any, are needed in the models?**
- **What are the implications for transport and mixing of trace gases and aerosols?**

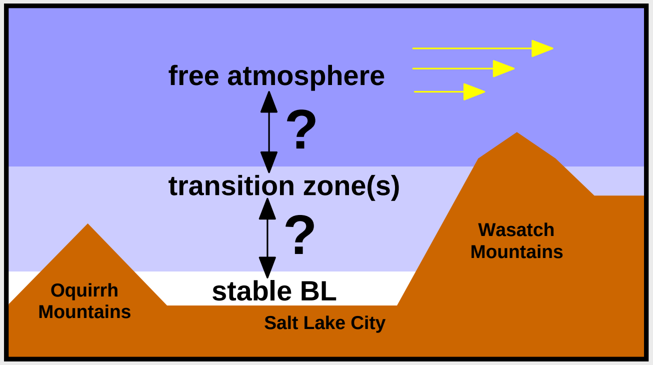
Motivation

Linking Local to Regional Scales



Aerosol Buildup during Morning Commute 0835 MST October 20





Meteorological Models

MM5: research model, part of EPA's MM5/CMAQ air quality modeling system

- **sigma-pressure vertical coordinate, $\Delta z_{sfc} \sim 30$ m**
- **initial and boundary conditions from NCEP/NCAR analyses**

RAMS: research model

- **sigma-height vertical coordinate, $\Delta z_{sfc} \sim 15$ m**
- **initial and boundary conditions from NCEP AVN analyses**

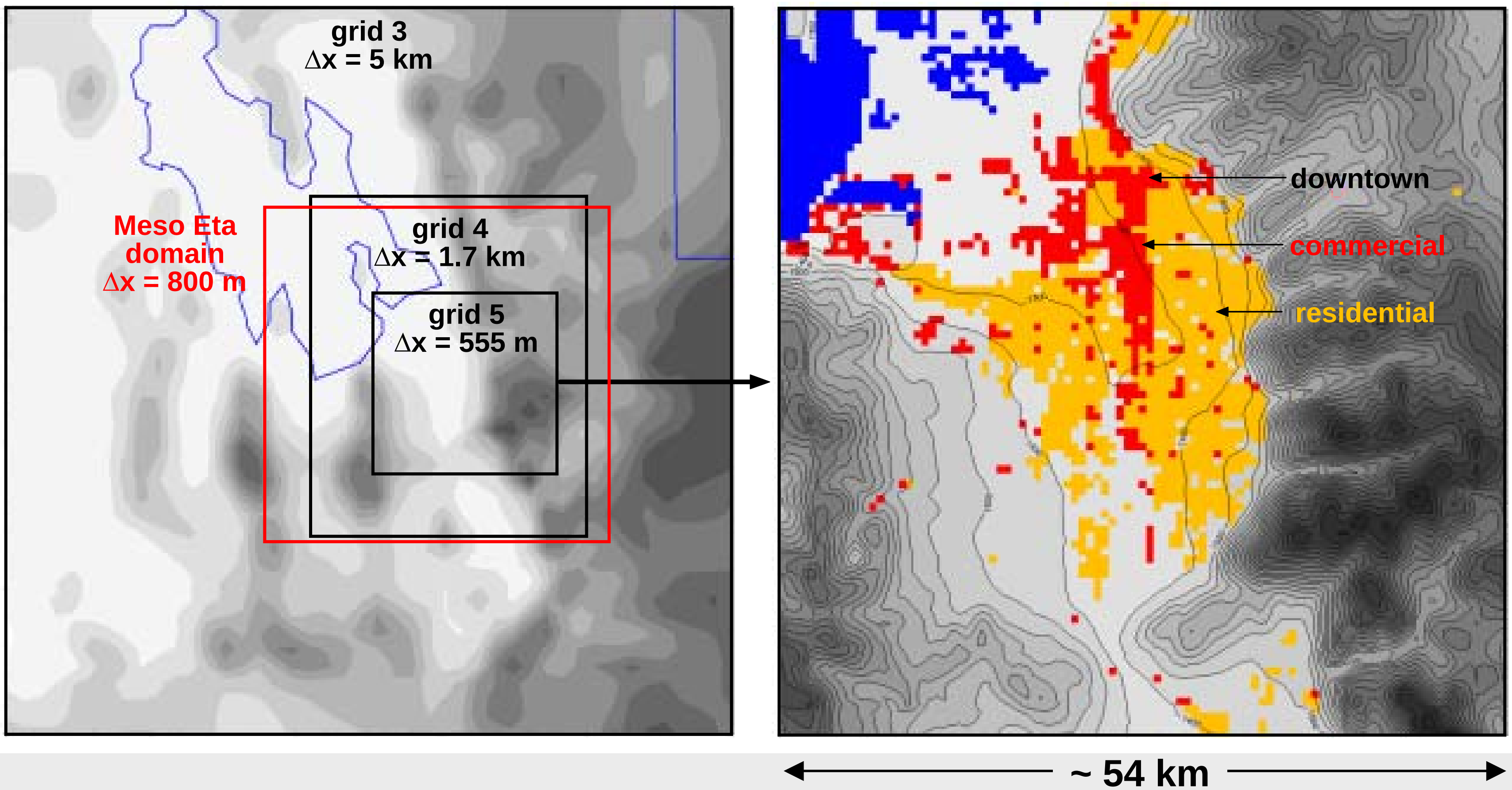
Meso-Eta: one of NCEP's operational forecast models for the U.S.

- **step-mountain vertical coordinate, $\Delta z_{sfc} \sim 30$ m**
- **initial and conditions from NCEP 32-km Eta analyses**

In this study, we ran the models with spatial resolutions and parameterizations as similar as possible. All models used similar turbulence closure based on a prognostic turbulence kinetic energy (TKE) equation, but other parameterizations (radiation, clouds, land-use) were different.

Model Domains

MM5 and RAMS grid 3 | **MM5 and RAMS grid 5**



grid 1, western U.S. Δx = 45 km
grid 2, Utah Δx = 15 km

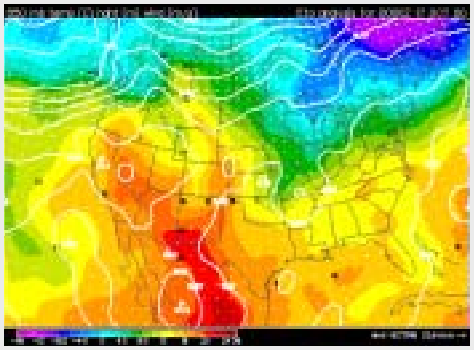
USGS land-use courtesy of John Leone, LLNL

Numerical Experiments

There were 10 Intensive Observation Periods (IOPs) during the month-long VTMX field campaign. The IOPs were grouped into two categories: 1) well-developed drainage circulations with weak synoptic conditions and 2) drainage circulations modulated by synoptic weather systems. All three models run for:

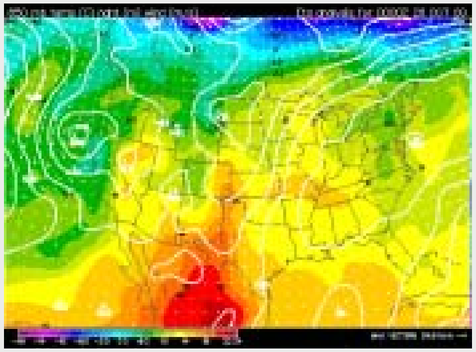
Case 1: two consecutive days, IOP 6 - 7

- **weak synoptic forcing**
- **winds at 700 hPa < 5 m s^{-1}, except at end of IOP 7**
- **well-developed local thermally-driven circulations**
- **60-h simulation period starting at 12 UTC October 16**



Case 2: IOP 10

- **strong synoptic forcing**
- **winds aloft > 10 m s^{-1}**
- **no well-developed local thermally-driven circulations**
- **36-h simulation period starting at 12 UTC October 25**



➧ **RAMS also run for IOP 8**

Evaluation Criteria

"Traditional"

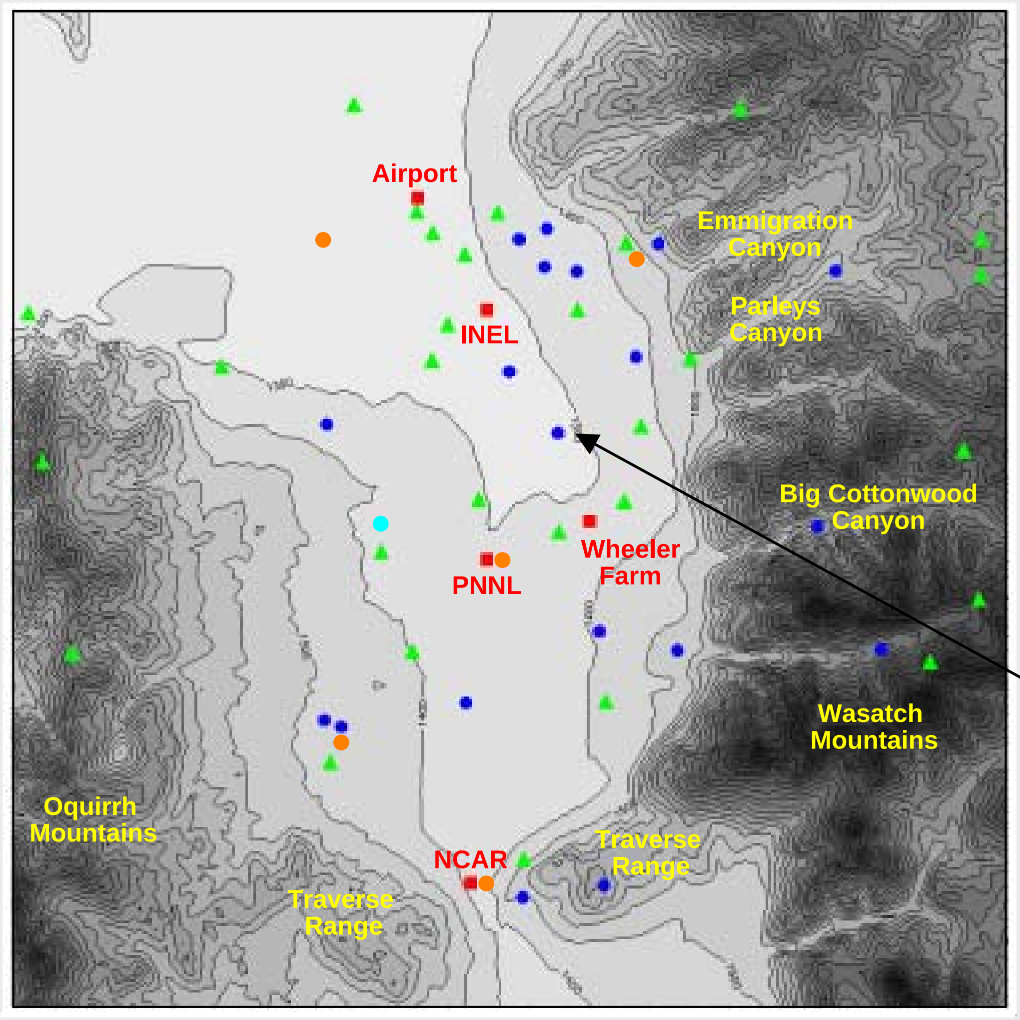
- **depth of convective and stable boundary layer, from *radiosondes***
  - **extent of daytime and nighttime vertical mixing**
- **surface wind field, from *surface monitoring network***
  - **horizontal transport, convergence/divergence**
- **wind profiles, from *radar wind profilers* and *radiosondes***
  - **horizontal transport**

"New"

- **multiple inversion layers, from *radiosondes***
  - **extent of vertical mixing in mid-valley atmosphere**
- **3-D horizontal wind fields, from *Doppler lidar***
  - **horizontal transport, convergence/divergence aloft**
- $-w\frac{\partial C}{\partial z}$ **vertical velocities, from *sonic anemometers* and *sodars***
  - **vertical transport**
- $\frac{\partial}{\partial z}K\frac{\partial C}{\partial z}$ **TKE, from *sonic anemometers* and *radar wind profilers***
  - **vertical mixing**

in meteorological models, these are subject to small errors in horizontal winds and vertical wind and temperature gradients

Observations

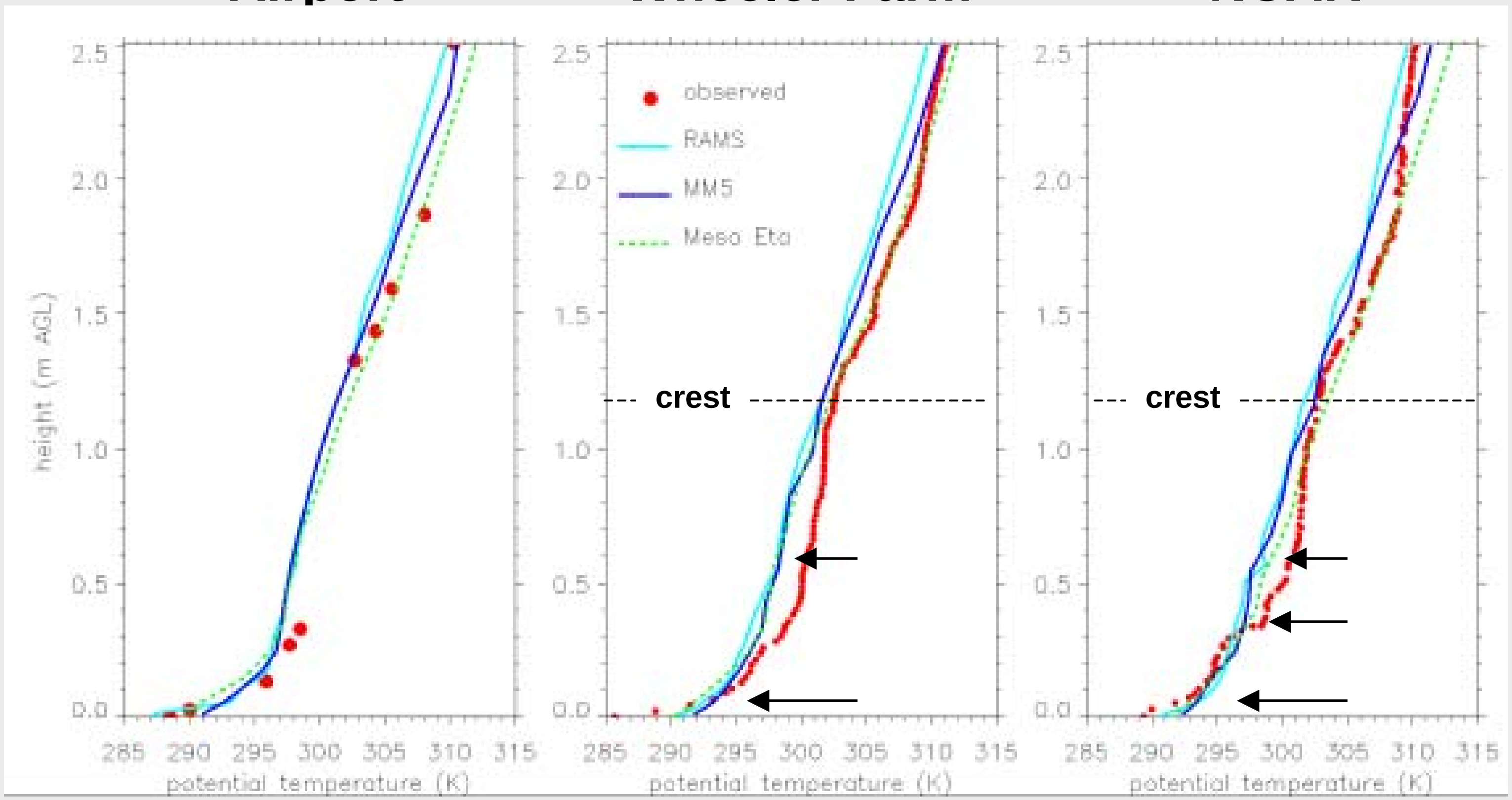


- MesoWest surface meteorological stations
- VTMX / CBNP surface meteorological stations
- VTMX / CBNP vertical profilers
- VTMX sonic anemometers
- VTMX Doppler lidar

Morning Temperature Profiles

IOP 6, 12 UTC October 17 (05 MST)

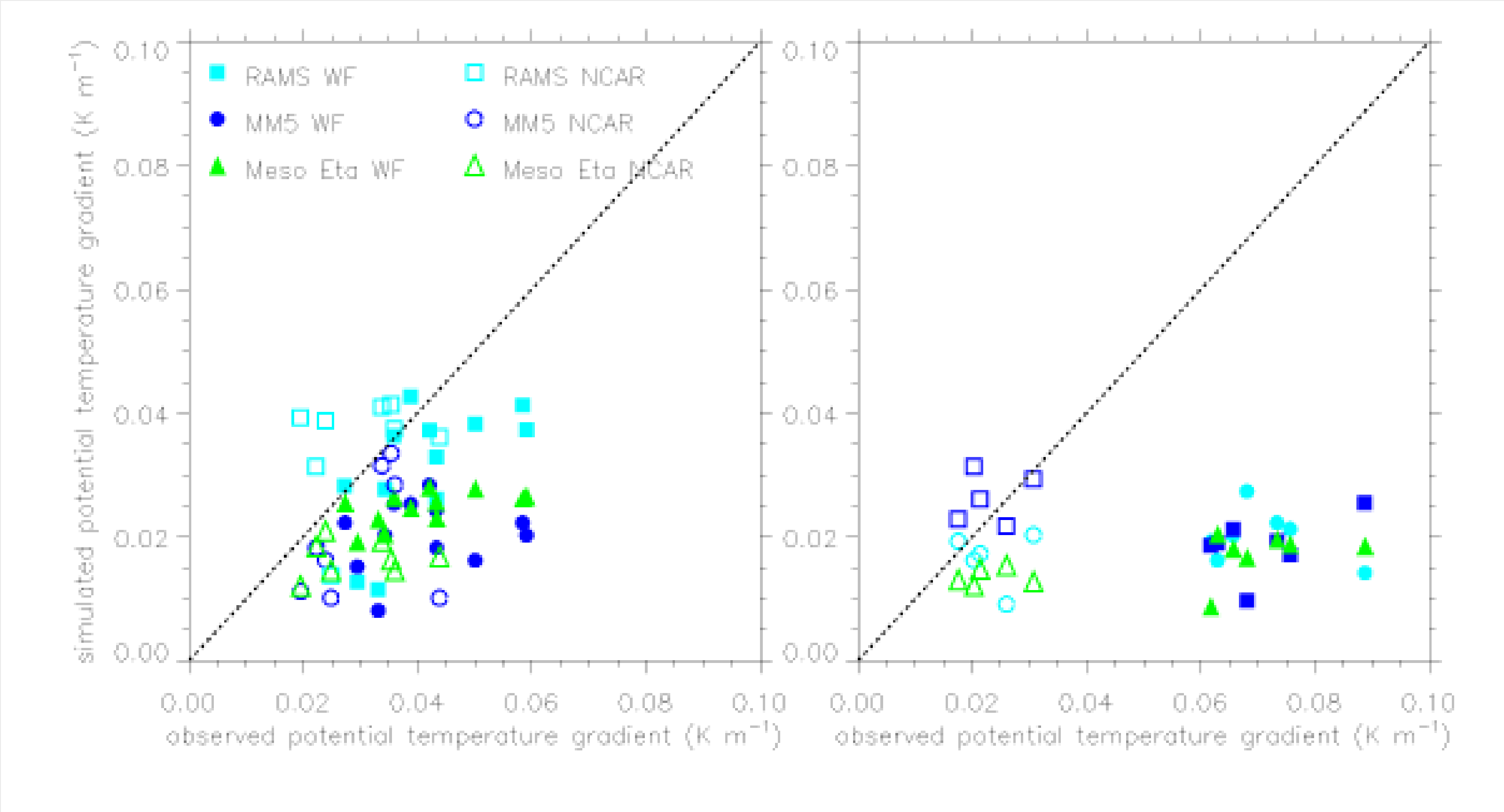
Airport **Wheeler Farm** **NCAR**



- **surface gradient in potential temperature, $\theta = T(p_o/p)^{R/cp}$, smaller than observed**
- **simulated θ too low in mid-valley atmosphere**

Surface Temperature Gradients

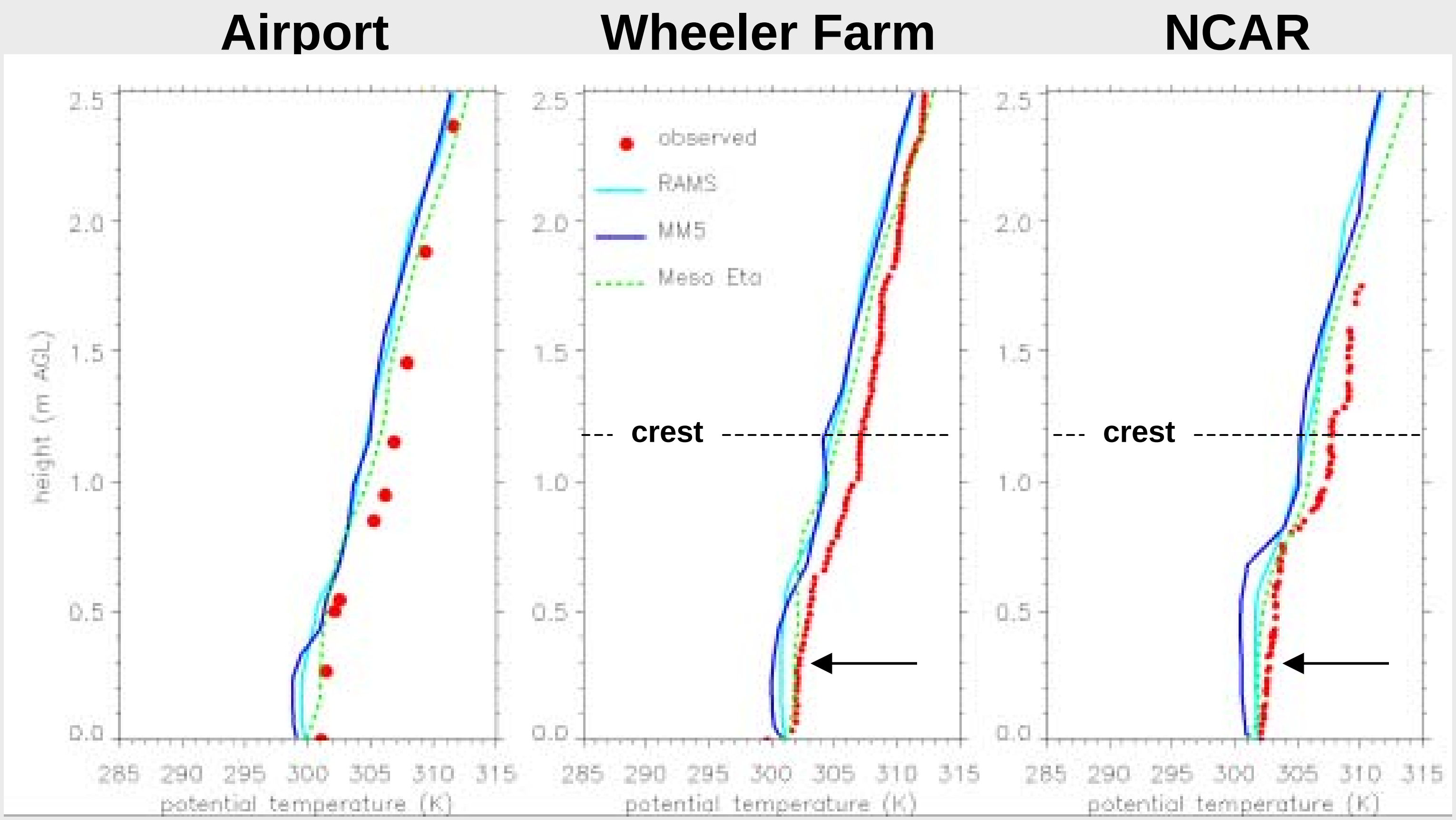
IOP 6 and 7 | IOP 10



- **Wheeler Farm usually had the largest vertical temperature gradients**
- **all of the models usually underestimated near-surface θ gradient**

Afternoon Temperature Profiles

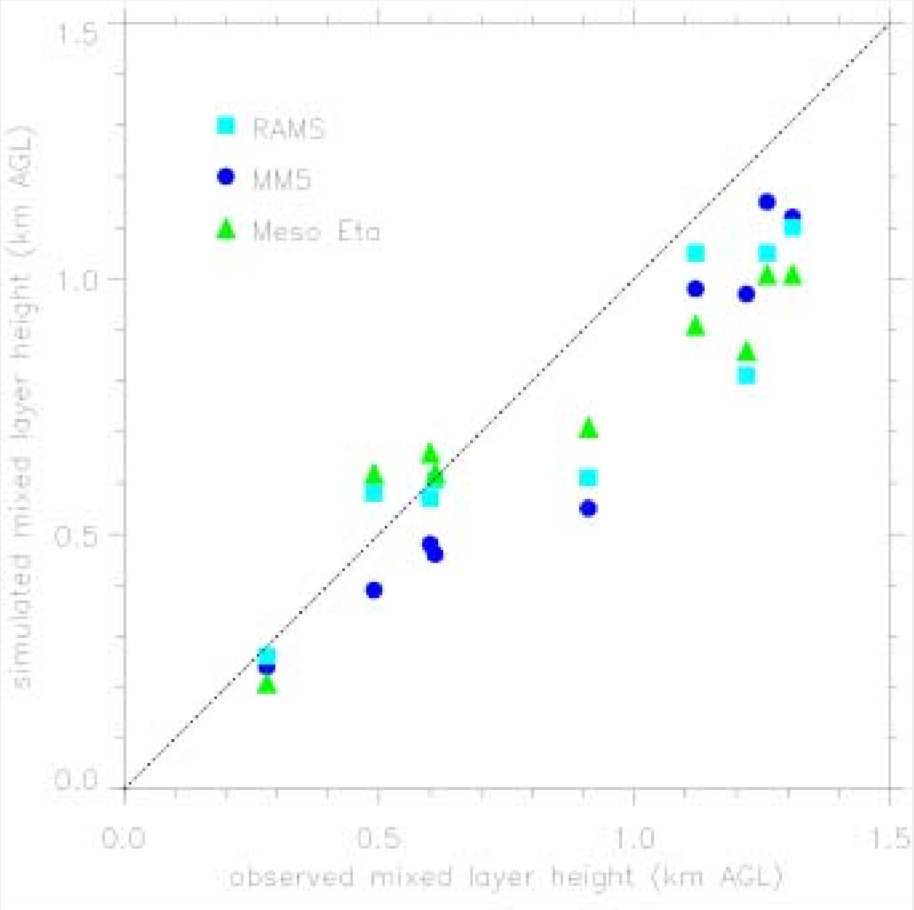
IOP 7, 00 UTC October 18 (17 MST)



- **simulated θ in convective boundary layer too low**

Mixed Layer Depths

IOP 6 and 7

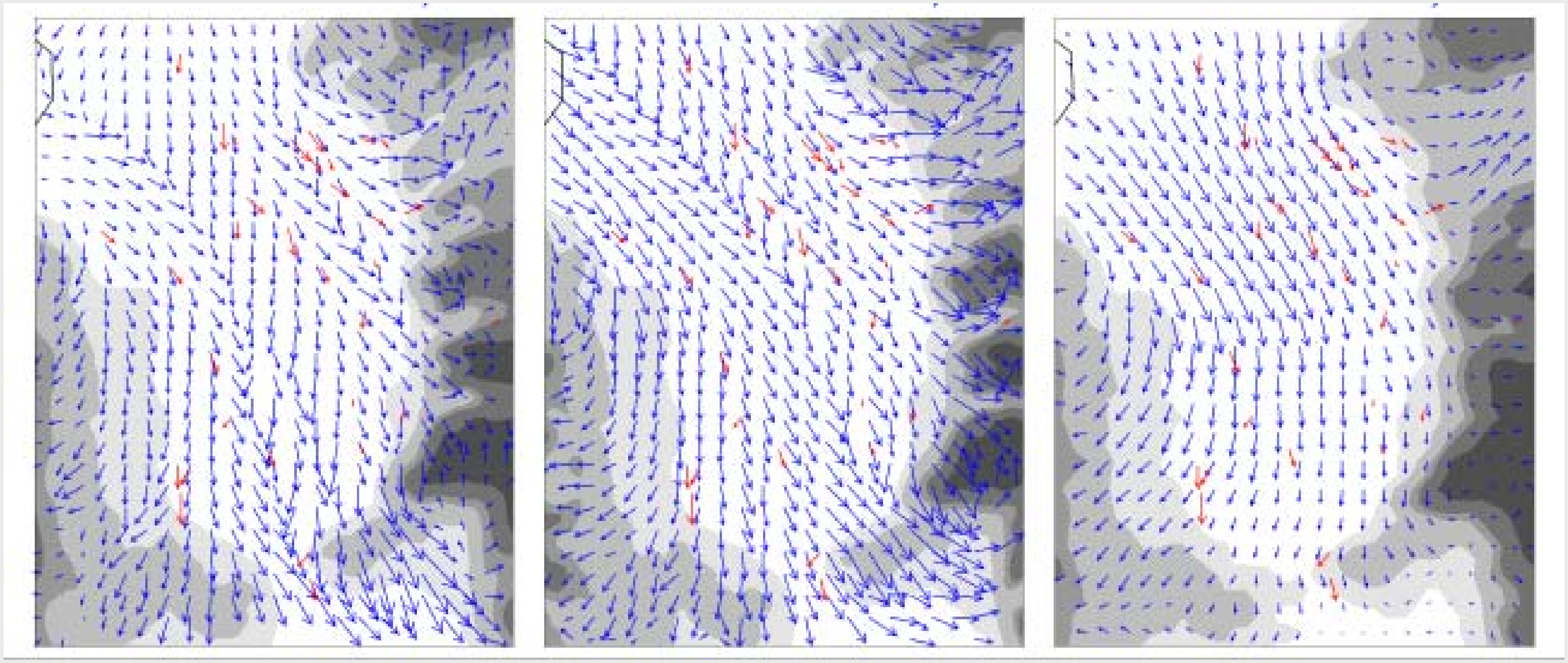


- **predicted mixed layer depths similar to observed during the morning, but ...**
- **mixed layer depths too low during the afternoon**

Afternoon Surface Wind Fields

IOP 6, 23 UTC October 16 (16 MST)

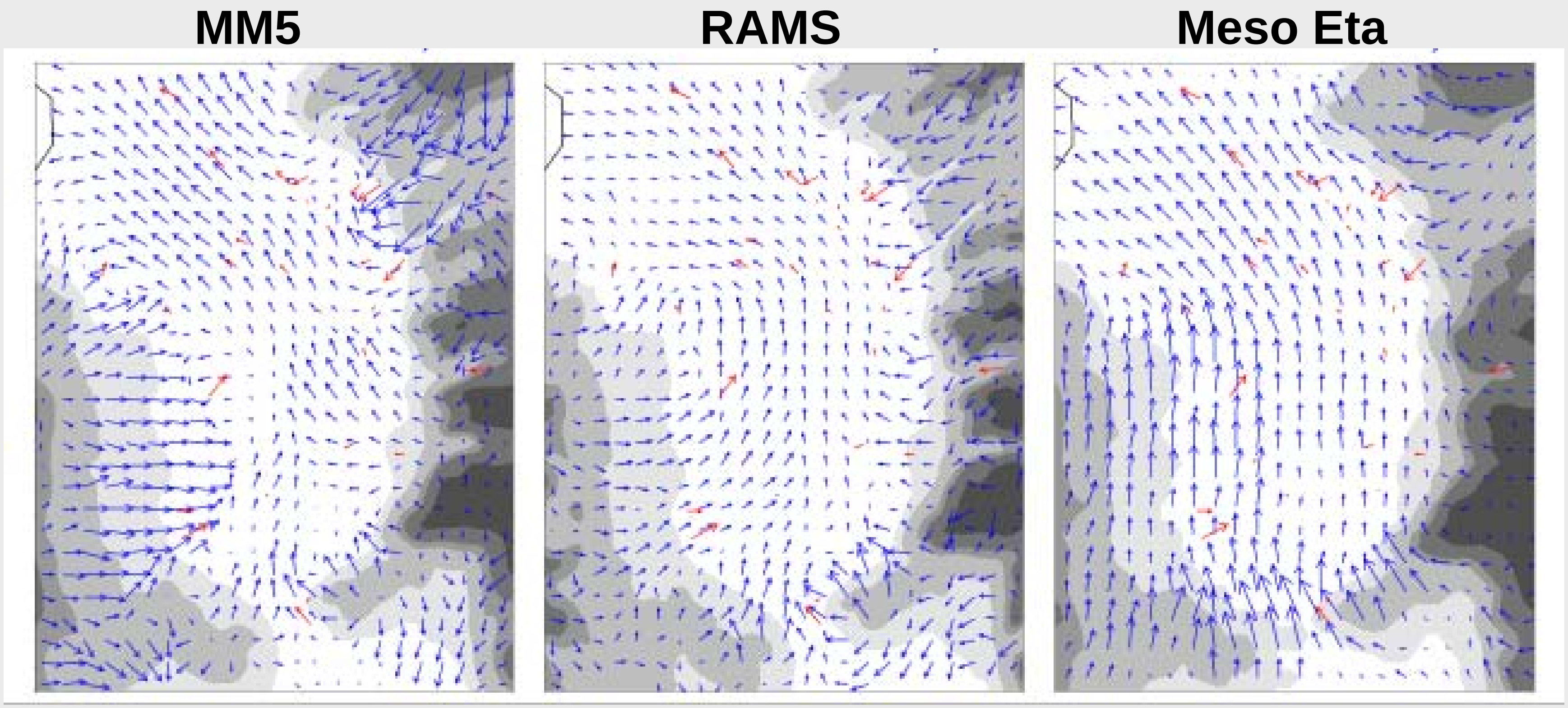
MM5 **RAMS** **Meso Eta**



- **predicted northerly up-valley flow from all three models similar to observed**
- **MM5 and RAMS produced convergence zones along the valley floor**

Nighttime Surface Wind Fields

IOP 6, 09 UTC October 16 (02 MST)

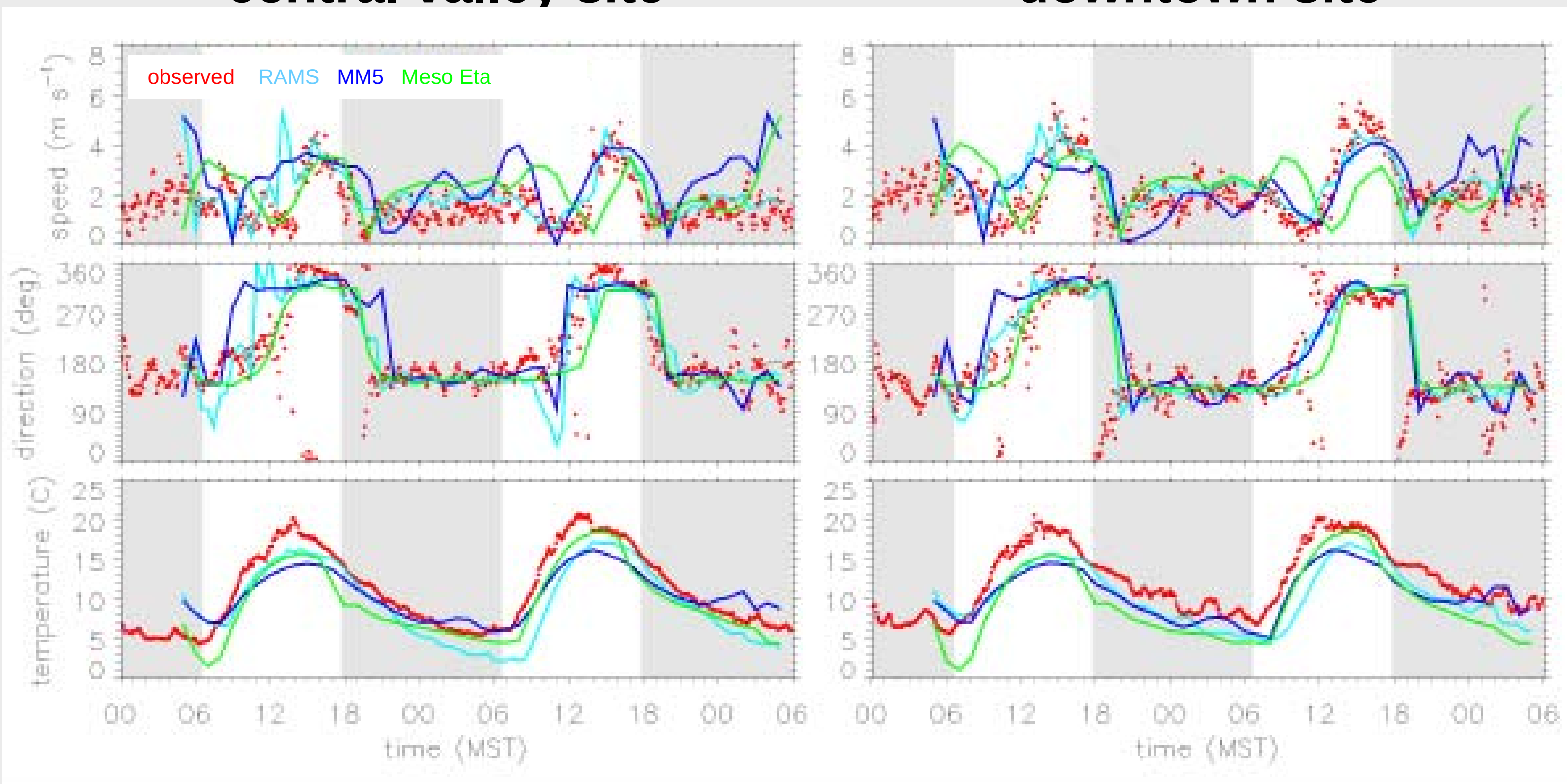


- **predictions of down-valley flow from MM5 and RAMS better than Meso Eta**
- **Meso Eta nocturnal winds "smoother" than the other models**

Surface Diurnal Variations

Wind Speed, Direction, and Temperature during IOP 6 - 7

central valley site **downtown site**



- **shift to northerly up-valley winds occurred 2 - 4 h too soon in RAMS and MM5**
- **all models have a cold bias**

Surface Meteorology Statistics

IOP 6 and 7

temperature bias (C)

time	RAMS	MM5	Meso Eta
day	-1.63	-1.15	-2.33
night	-0.30	-0.23	-1.21
all	-0.95	-0.70	-1.77

wind speed bias (m s^{-1})

time	RAMS	MM5	Meso Eta
day	0.33	0.50	0.18
night	0.19	0.43	0.08
all	0.26	0.46	0.13

wind direction bias (deg)

time	RAMS	MM5	Meso Eta
day	-7.17	6.52	-9.88
night	4.50	13.35	11.73
all	-1.38	9.91	0.85

IOP 10

temperature bias (C)

time	RAMS	MM5	Meso Eta
day	-1.44	-0.42	-1.54
night	-1.53	-1.21	-3.03
all	-1.47	-0.74	-2.14

wind speed bias (m s^{-1})

time	RAMS	MM5	Meso Eta
day	-0.37	-0.62	1.85
night	0.17	0.28	1.31
all	-0.16	-0.26	1.64

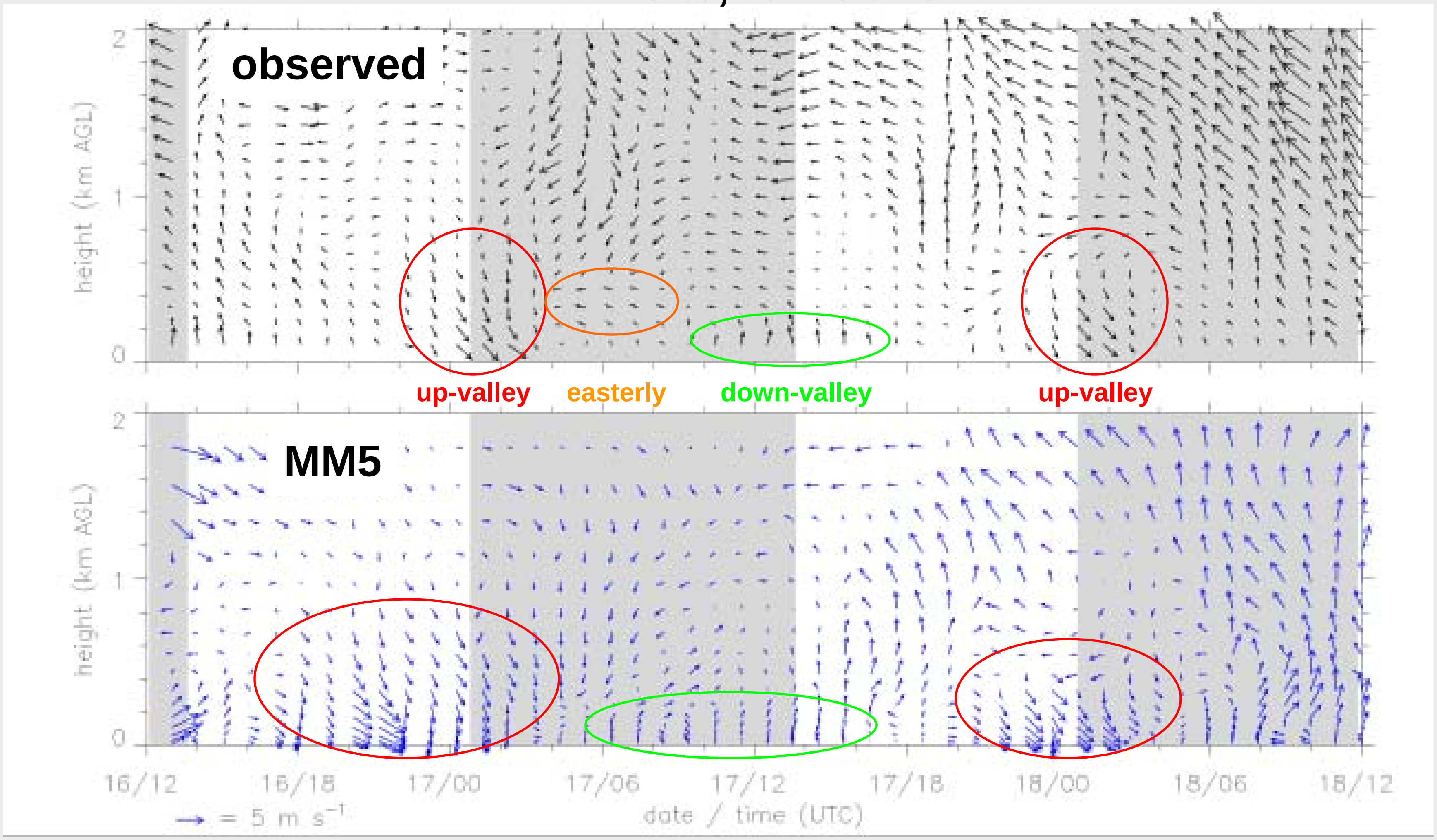
wind direction bias (deg)

time	RAMS	MM5	Meso Eta
day	-2.33	4.79	-3.58
night	6.87	2.99	15.28
all	-4.13	4.10	3.89

- 36 stations used, RMS error and standard deviation of errors also computed
- all models have a cold bias; winds are deceptively good
- only small differences in the statistics for valley floor, valley slopes, and mountain sites, except smallest errors in Meso Eta were over valley floor sites

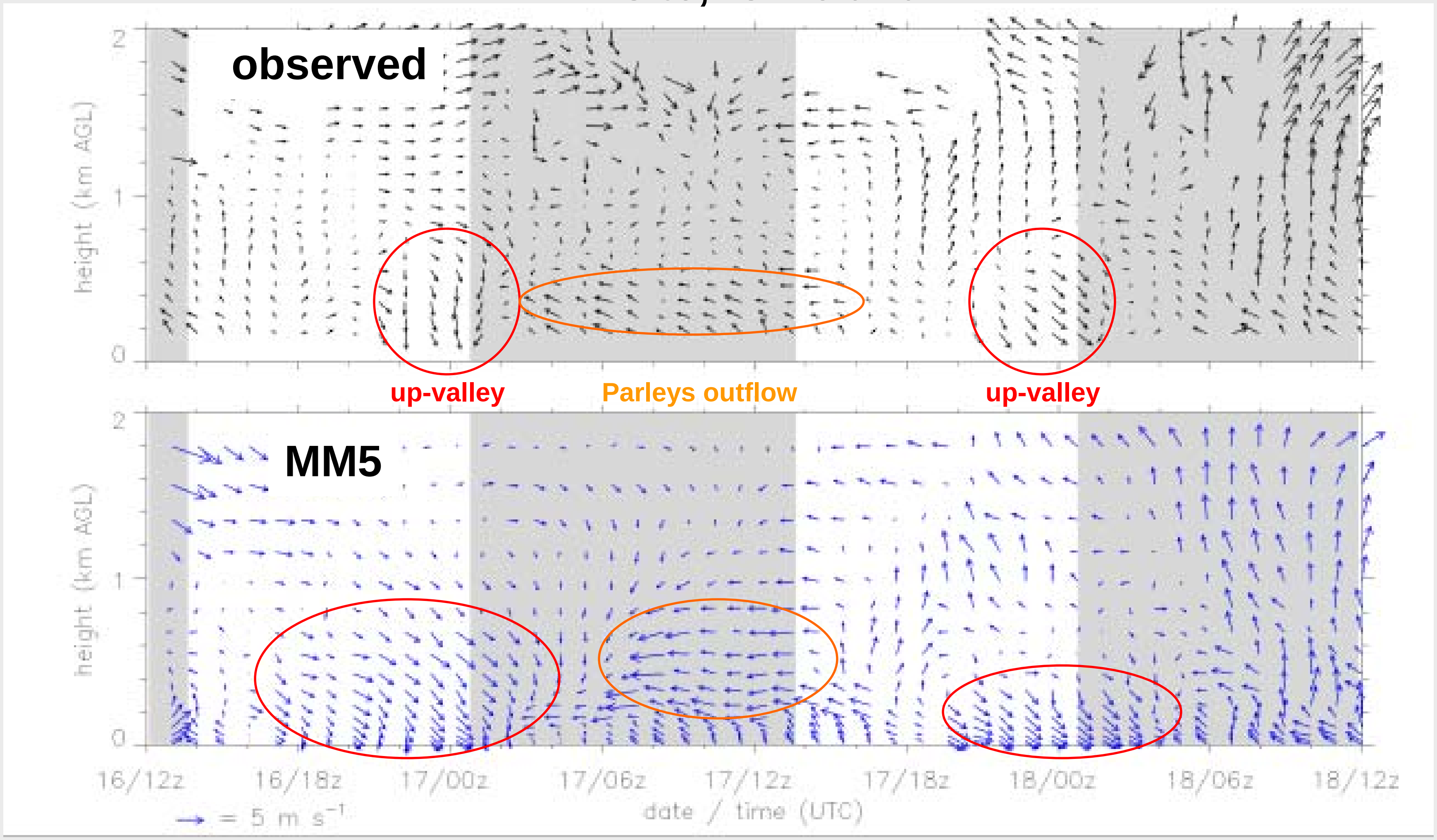
Wind Profiles

PNNL site, IOP 6 and 7



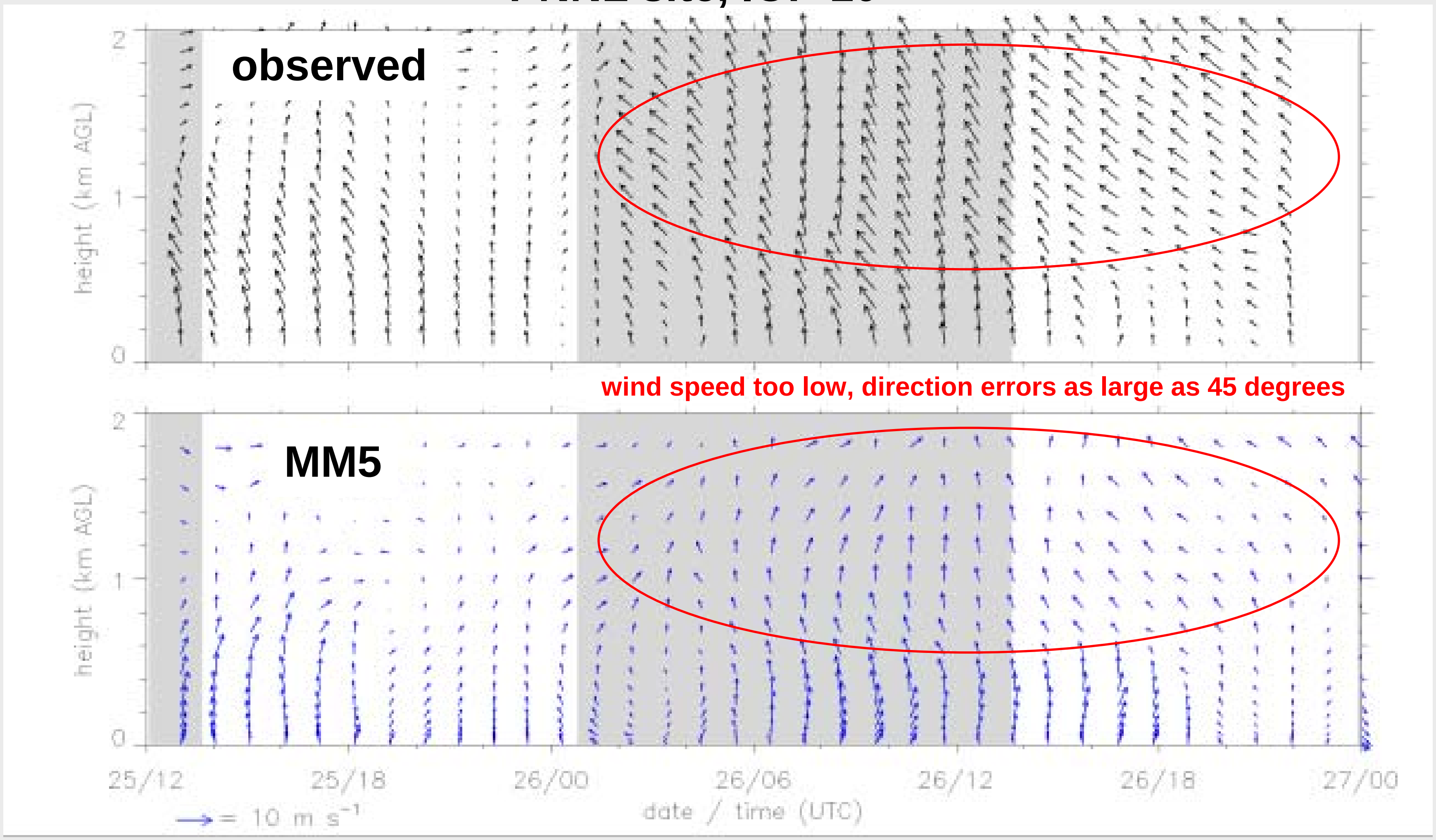
Wind Profiles

INEL site, IOP 6 and 7



Wind Profiles

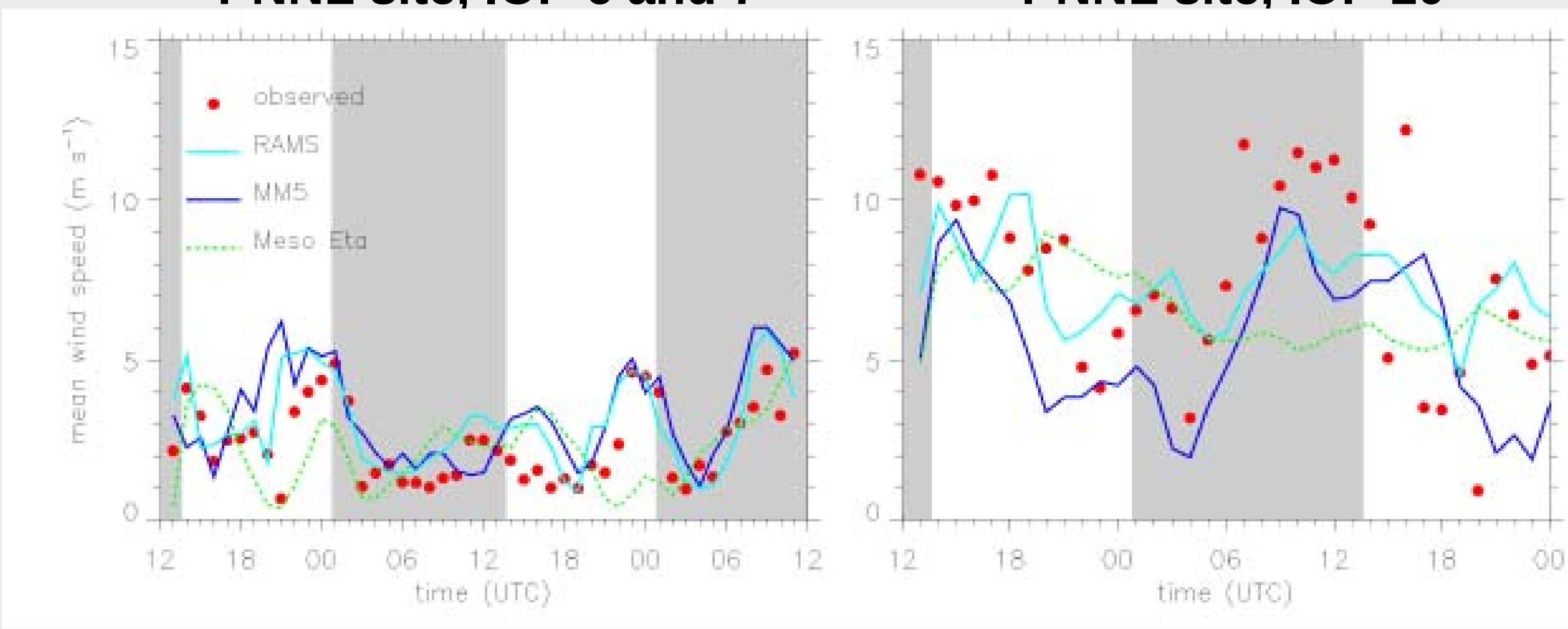
PNNL site, IOP 10



Diurnal Variations Aloft

Average Observed and Predicted Wind Speed within 500 m of the Ground

PNNL site, IOP 6 and 7 **PNNL site, IOP 10**

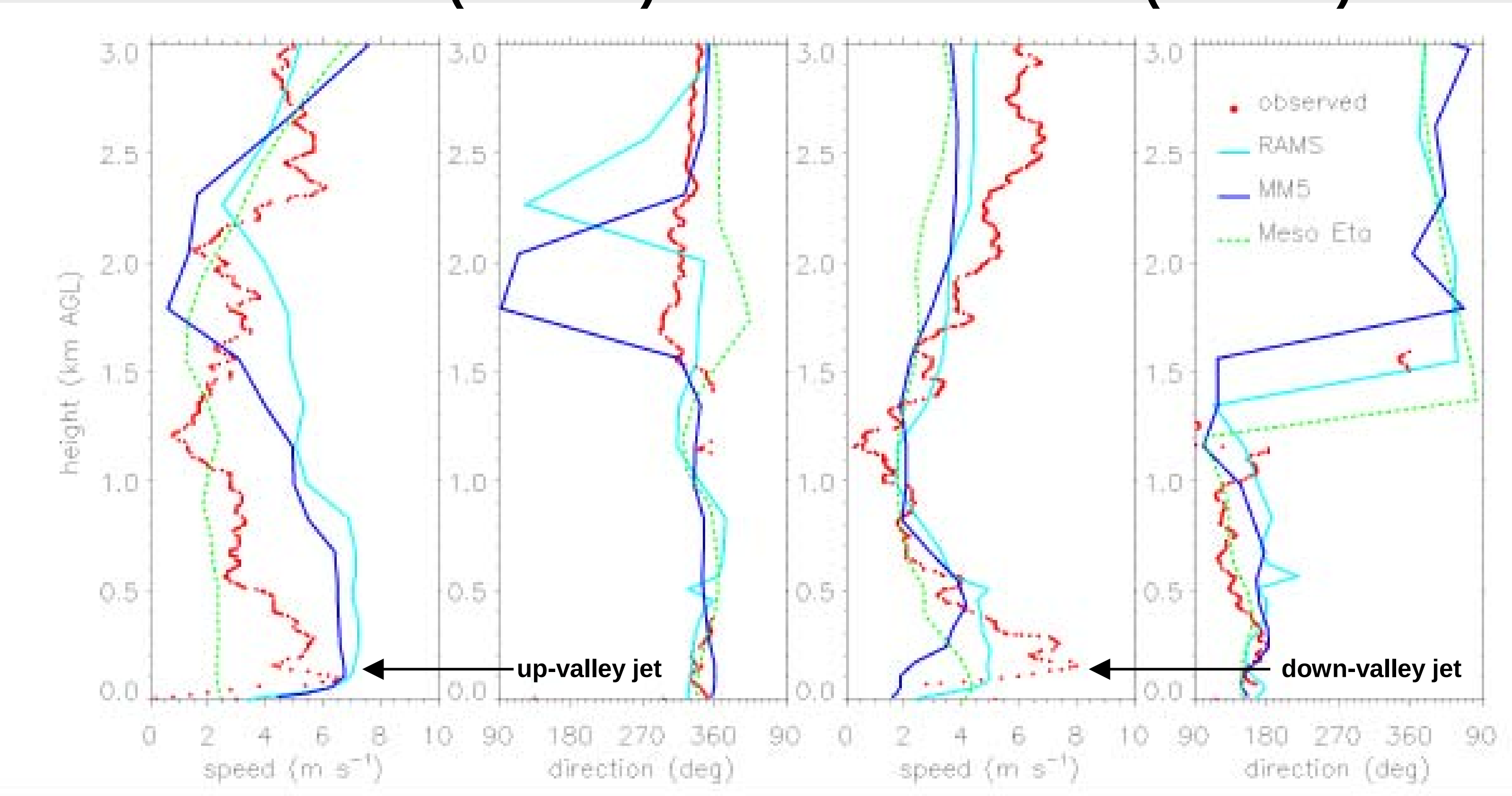


- **under weak synoptic forcing, diurnal evolution and peak afternoon wind speed well predicted (except for Meso Eta), but surprisingly ...**
- **large wind speed errors during IOP 10 when synoptic forcing was strong**

Gap Wind

IOP 6, October 17, NCAR Site

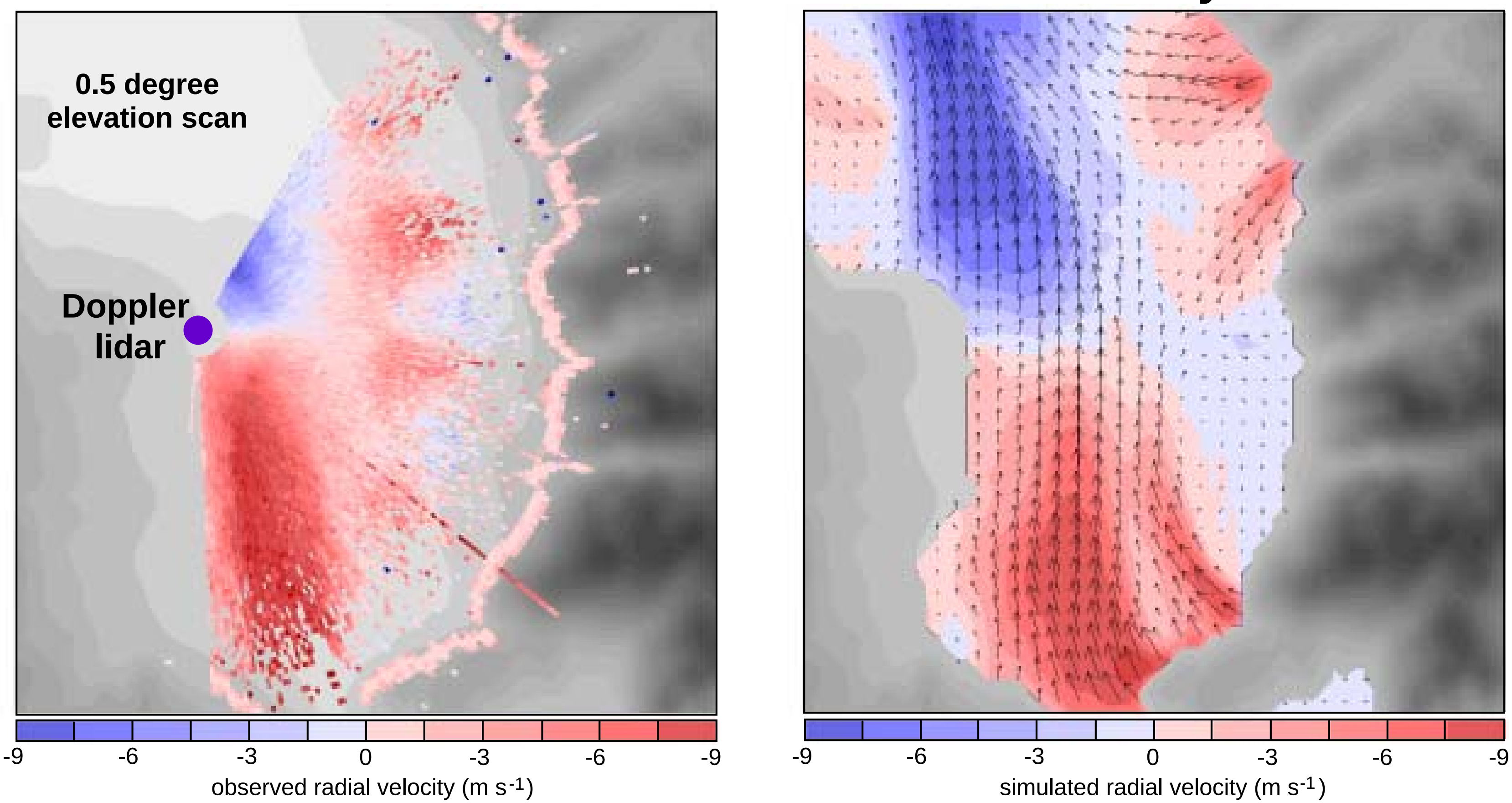
00 UTC (17 MST) **12 UTC (05 MST)**



3-D Wind Field

IOP 8, 13 UTC October 20 (06 MST)

Observed | **Simulated by RAMS**

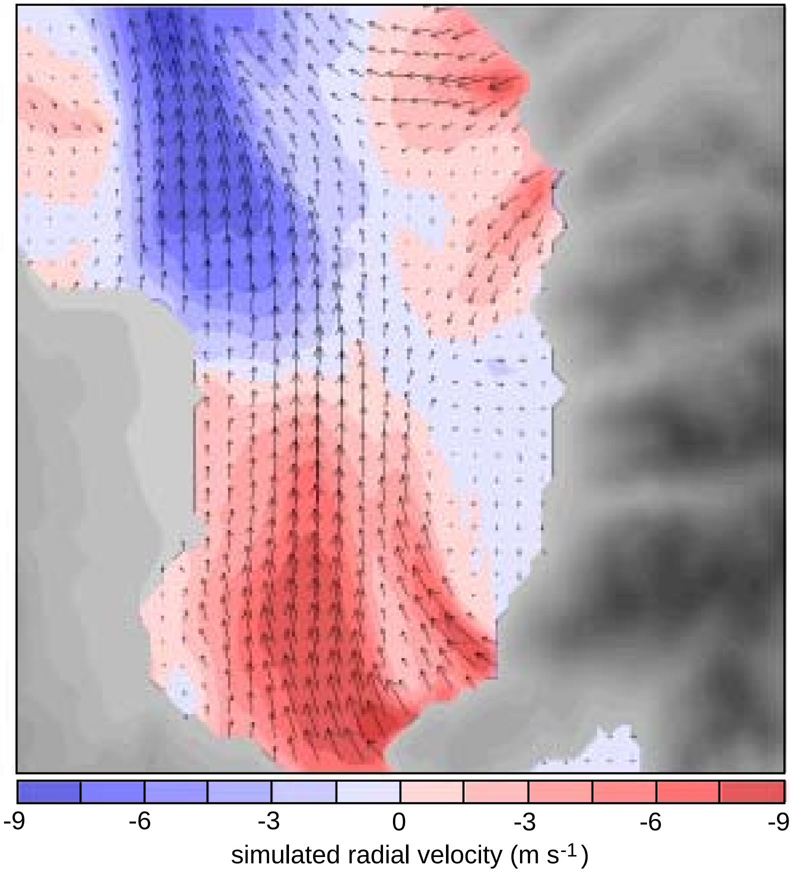


courtesy of Lisa Darby and Bob Banta, NOAA/ETL

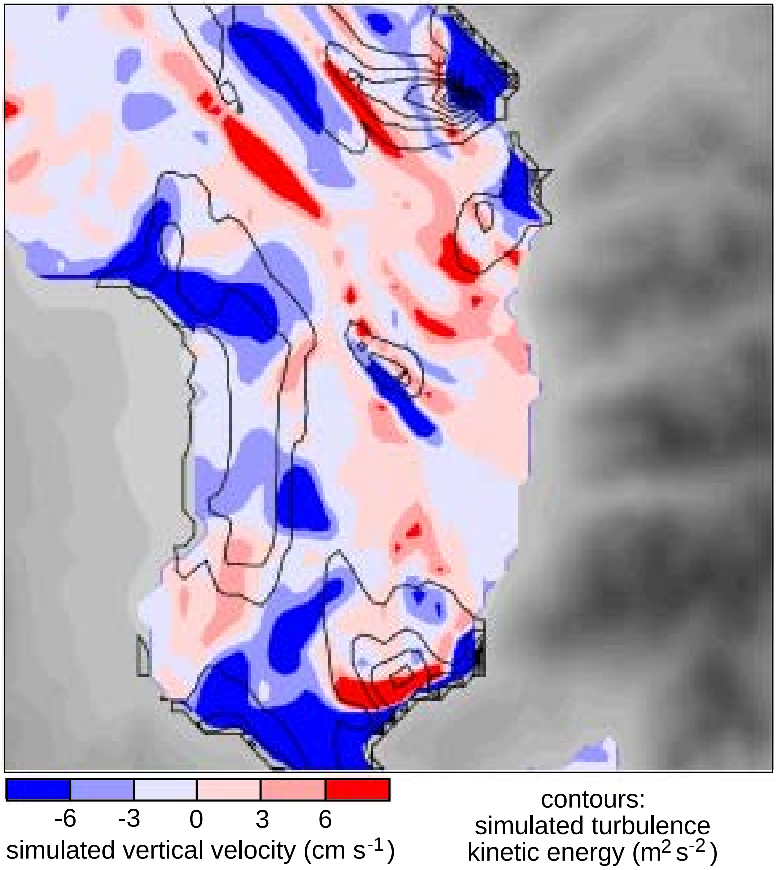
Inferred Vertical Mixing

IOP 8, 13 UTC October 20 (06 MST)

Simulated Horizontal Winds



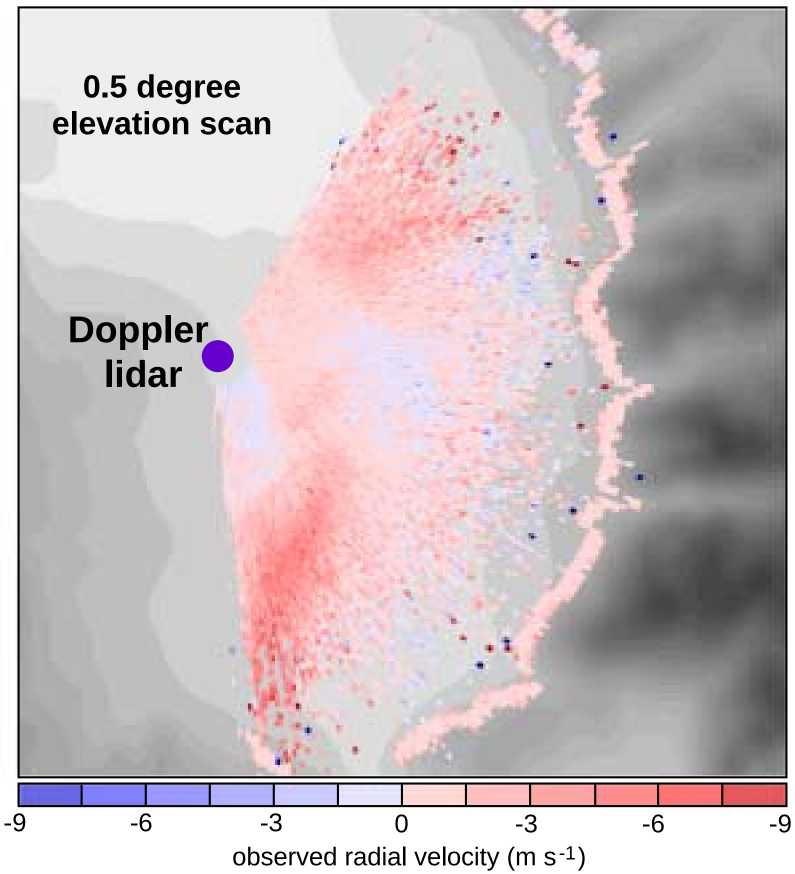
Simulated Vertical Mixing



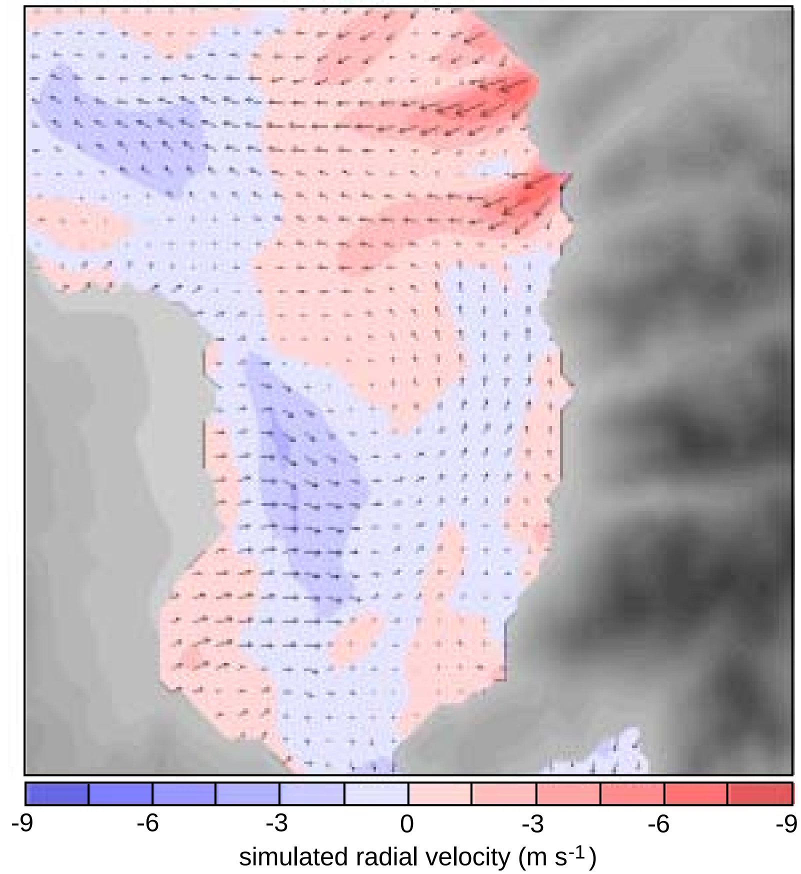
3-D Wind Field

IOP 8, 08 UTC October 20 (01 MST)

Observed

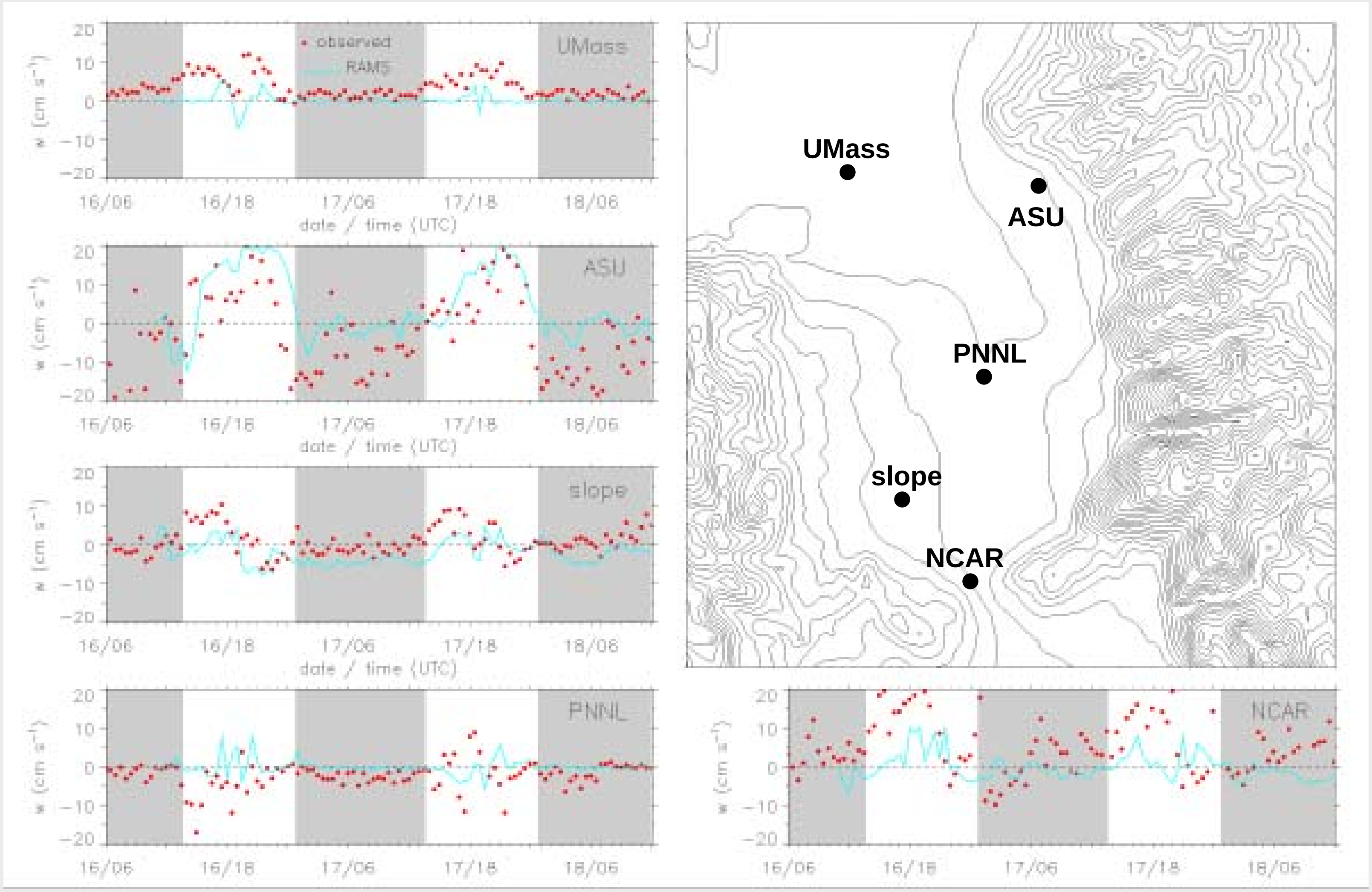


Simulated by RAMS



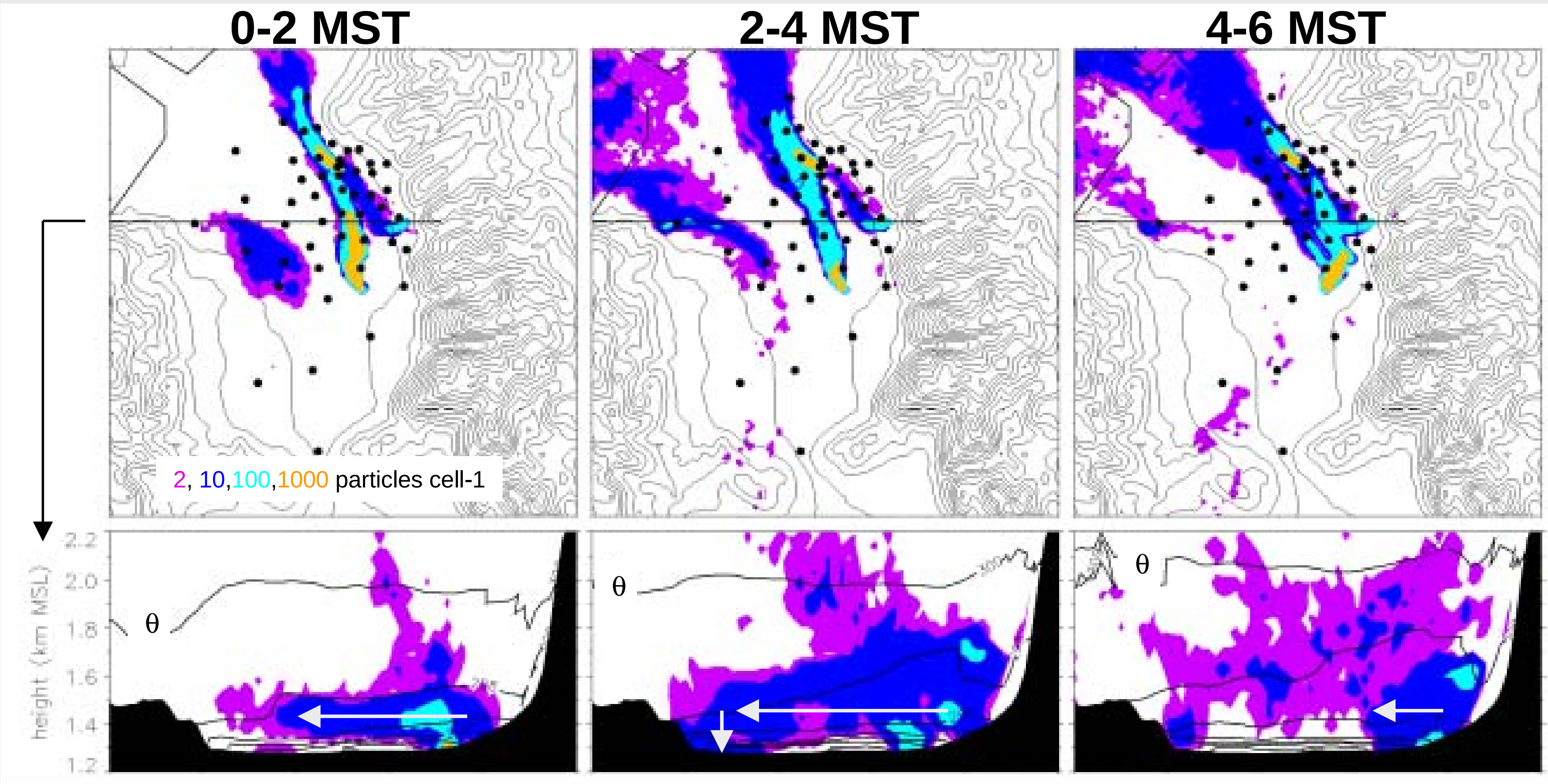
courtesy of Lisa Darby and Bob Banta, NOAA/ETL

Vertical Motions



Simulated PFT Evolution

IOP 8, 20 October: Surface Concentrations During Release Period



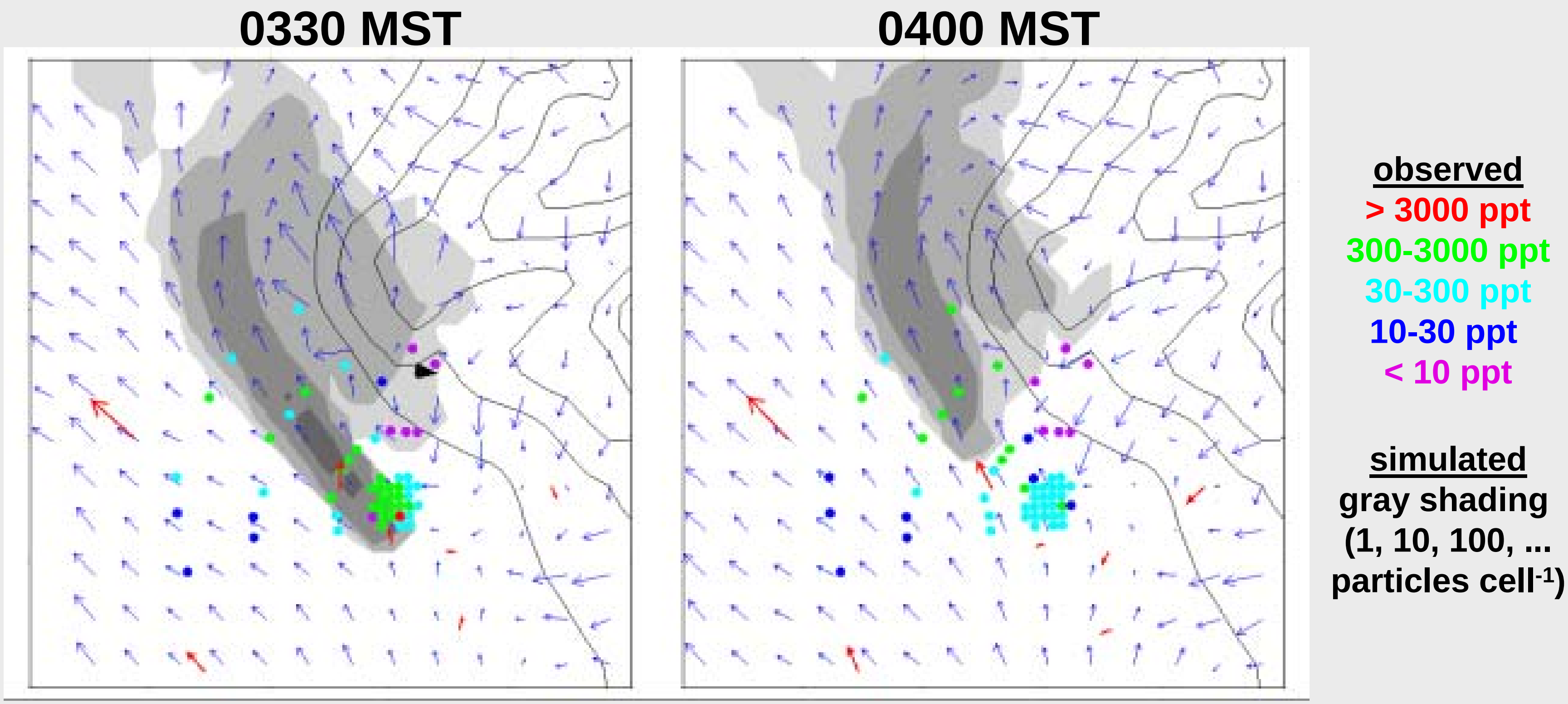
Parleys outflow transports particles over the cold pool

particles mixed to the ground over the western valley slope

downvalley flow strengthens, Parleys outflow diminishes

Simulated SF_6 Plume

IOP 7, 18 October: Surface Concentrations

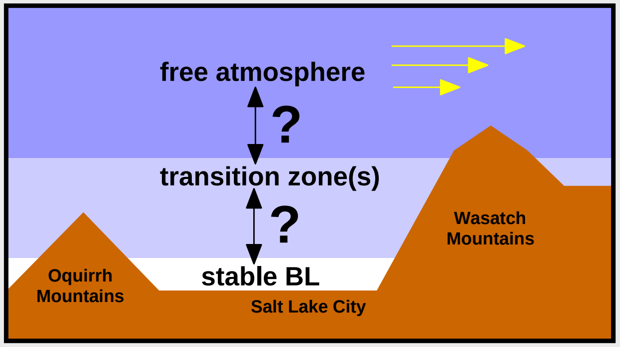


- observed tracers a valuable measurement to evaluate transport and mixing
- predicted plume direction and width very similar to observations at times, but plume often transported downwind too fast (predicted winds too strong)

Summary

All 3 models *qualitatively* capture the diurnal evolution of the main circulations in the valley (daytime up-valley flow, nighttime down-valley flow, jets from canyons and through gaps). The complex converging/diverging flows compared quite well at times with surface network and lidar observations. Nevertheless, large errors occurred that can significantly affect our understanding of local transport and mixing of trace gases and aerosols in urban valleys including:

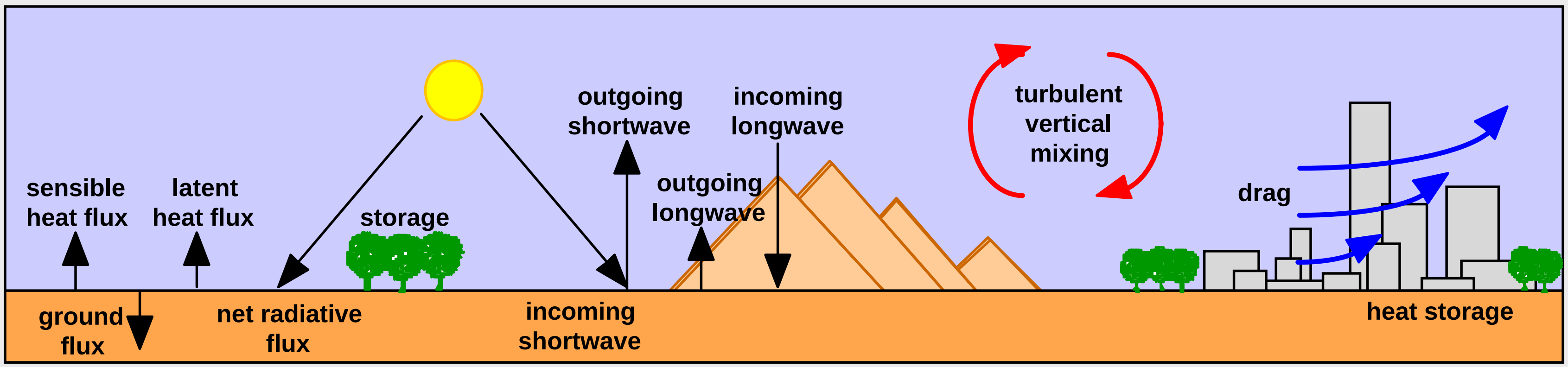
- **cold bias at the surface and aloft; larger during the day for IOP 6-7, but larger at night for IOP 10**
- **late afternoon mixed layer depths too low**
- **nocturnal boundary layer deeper than observed and the vertical θ gradients were too low**
- **onset of northerly up-valley flow occurred 2 - 4 h too early in RAMS and MM5**
- **large errors in mid-valley atmosphere winds, models fail to adequately represent interactions of ambient winds and the topography**
- **RAMS and MM5 outperformed Meso Eta, but the types of forecast errors were surprisingly similar**



Model Improvements

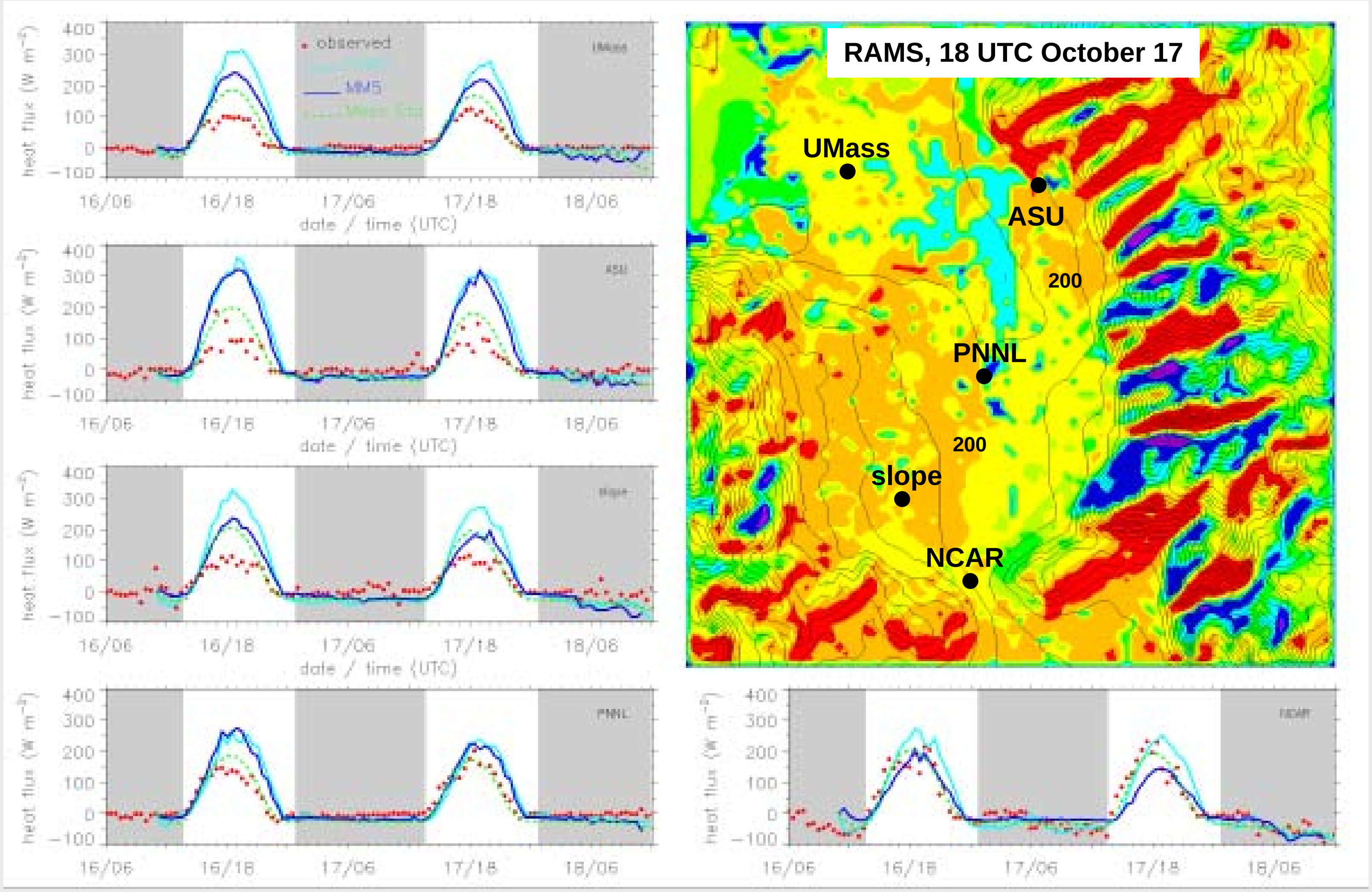
What are the likely sources of model errors?

- surface layer parameterization
- turbulence parameterization
- radiation parameterization
- urban canopy parameterization

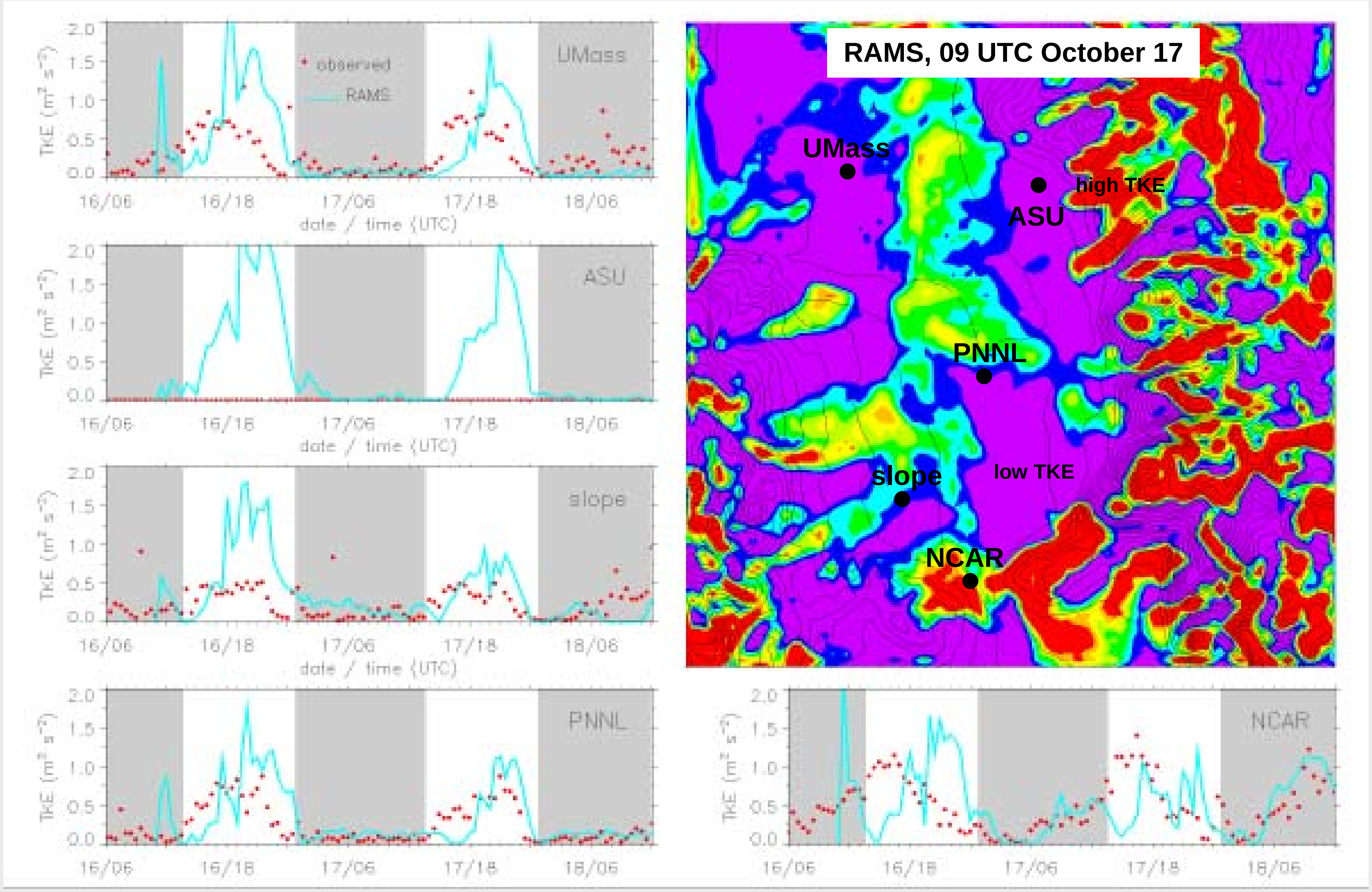


- Small errors in winds and temperatures can lead to large errors in vertical transport and mixing; therefore, improvements in these areas are needed to more adequately describe how trace gases and aerosols are mixed within urban valleys.

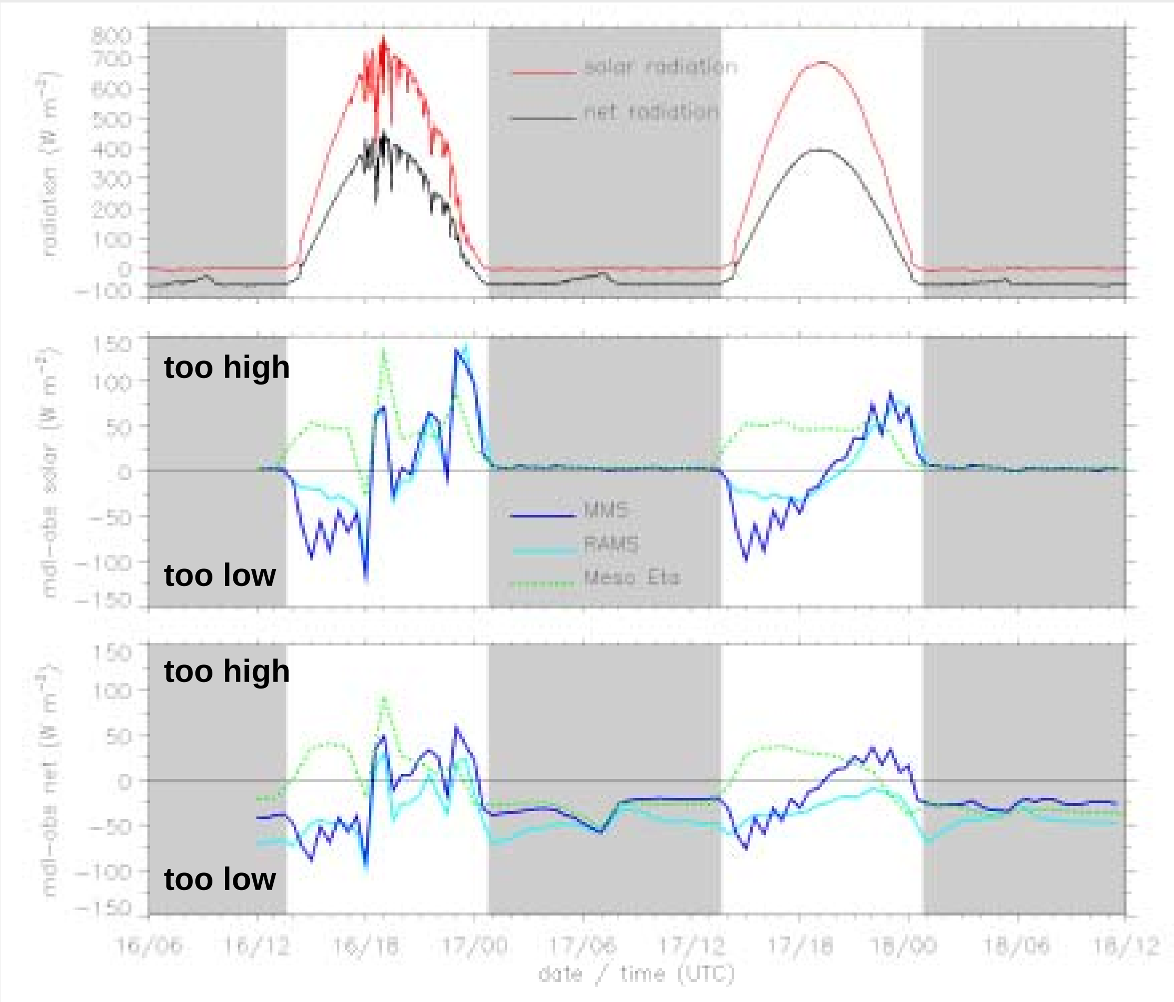
Sensible Heat Flux



Turbulence Kinetic Energy



Radiation

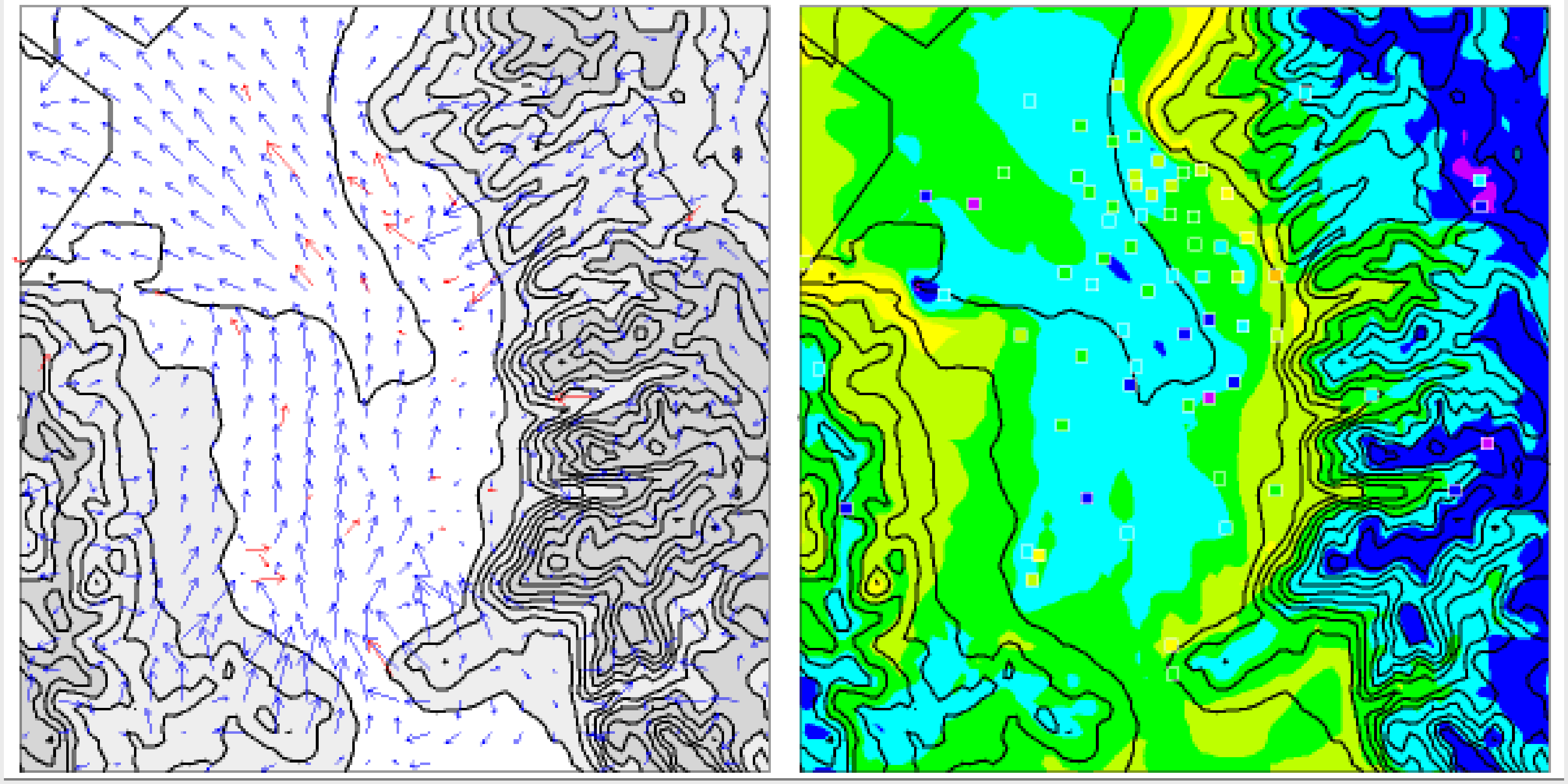


- MM5 and RAMS too low during morning and too high during afternoon by ~ 5%, while Meso Eta too high all day
- all three models overestimate net radiation at night by a factor of 2
- results imply that $R_L\downarrow$ too low at night

net = $(1\text{-}A)^*R_S\downarrow + R_L\downarrow - R_L\uparrow$

Urban Effects

Observations and Predictions at 13 UTC October 20 (06 MST)



observed **predicted ~ 15 m AGL**
topography - contours

observed - ■ **predicted - contours ~ 15 m AGL**
< 2 2-4 4-6 6-8 8-10 10-12 12-14 >14 C

Next Step

- to our knowledge, this is the first evaluation and comparison study of three state-of-the-art mesoscale models at sub-kilometer grid spacing
- this was an important first step to identify areas of improvements needed to more accurately represent dispersion processes for trace gases and aerosols
- meteorology is often taken as a given in chemistry models - but errors in predicted wind, temperature, humidity, and turbulence fields can affect the conclusions drawn from chemistry models
- we have identified measurements for the next VTMX field campaign needed to resolve model errors

Next steps of this research include:

- use PFT data to fully evaluate transport and mixing in present simulations
- modify mesoscale models and use VTMX observations to evaluate
  - surface layer parameterization
  - turbulence parameterization (including transfer knowledge LES and DNS models)
  - radiation parameterization
  - urban canopy parameterization